ON THE DEGREE OF COLLECTIVIZATION OF INTERACTION OF RELATIVISTIC HADRONS WITH NUCLEI

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Based on the analysis of data on the cumulative meson production, production of muon pairs and of particles with large transverse momenta on nuclei, it is shown that the mechanism of coherent interaction of hadrons with nucleon tubes is not realized.

1. Introduction

The problem of describing the interaction of relativistic hadrons with nuclei is still of great interest, because it is closely related to the space-time aspects of the strong interaction. One of the practical consequences of the study of this process is the rejection of simple cascade schemes which failed to describe a series of effects caused by the space-time factors (for the latter see Refs. [1, 2]).

Indeed, a more correct and consistent consideration of these factors allows one to overcome serious difficulties in describing the regularities of the dominating channel, multiple production in hadron-nucleus interactions [3–7] and of a rarer but very interesting and important class of processes, the processes of a collective, cumulative type [8–10].

At the same time we think that some reports go to extremes by overestimating the role of the finite dimension of the space-time interval, in which the process of production occurs, and by trying to oversimplify the problem.

An example of such an extreme trend is the model of the "coherent" tube which is widely discussed [11–15]. This model assumes that an incident hadron interacts with all the nucleons simultaneously which are in the tube with the cross section $\approx \sigma_{\rm NN}^{\rm in}$ and length which equals the path of its motion in nuclei. The interaction is considered as a collision of two hadrons with masses $m_{\rm h}$ and $\nu m_{\rm N}$, where $m_{\rm h}$ is the mass of an incident hadron, $m_{\rm N}$ is the mass of a nucleon and ν is the number of nucleons in the "tube". Thus, it is assumed that:

$$F_i(\nu, E) = F_i(1, \nu E), \tag{1}$$

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where F_i is a set of characteristics describing the result of interaction. In papers [11–15] an essential comparison is made between the model of coherent tube and the experimental data: the distribution of the multiplicity of particles and the correlations between the numbers of particles of different types [11], A-dependence of particle yield with large $p_\perp$ [12], the spectra of recoil nucleons in the $\pi-\mathrm{Ne}$ interactions [13], and the production of $\mu^\pm$ pairs in the $\mathrm{p}-\mathrm{A}$ interactions [14].

Without discussing in detail to what extent the model of coherent tube is consistent with experiment, we note that the problems under consideration are insufficient to prove its realization. The reason is that a number of important experiments which are crucial to the basic model assumption were not considered. In the present paper we discuss this problem.

2. *The model of "tube" and cumulative pion production*

The processes in which particles are produced with momenta kinematically inaccessible in the $\mathrm{h}-\mathrm{h}$ collisions [16] are called cumulative processes. This is due to their high sensitivity to the mechanism of collectivization and its degree in the hadron-nucleus collisions. For our purpose it is important that the spectra of these particles are measured with high accuracy [17–20].

At present the cumulative pion production is most completely studied at angle $\theta \approx 180^\circ$ in the interaction of protons (E_p up to approximately 9 GeV) with a large set of pure targets [17–20].

Let us describe such a process within the model of "coherent" tube. Assuming that the number of nucleons in a tube is distributed according to the law[1]

$$\varphi(n) = \frac{\nu^n}{n!} e^{-\nu}, \qquad \nu = \langle n \rangle,$$

and averaging over the impact parameter, for the cross section of the interaction with the tube containing n nucleons we find the following expression:

$$\sigma(n) = \frac{\pi}{2(\sigma\varrho)^2 n!} \int_0^{2\sigma\varrho R} \nu^{n+1} e^{-\nu} d\nu, \tag{2}$$

where σ is the cross section of the tube, ϱ is the nuclear matter density, and R the radius of a nucleus ($R = r_0 A^{1/3}$; $r_0 \approx 1.2$ fm).

The invariant cross section of cumulative π-meson production on the nucleus has the form

$$R_A(x) = \sum_{n=2} R_0(x_n, s_n)\sigma(n). \tag{3}$$

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[1] Sometimes the binomial distribution is used. However, it gives almost the same results as the Poisson φ distribution for $A > 10$.

According to (1) R_0 is the normalized invariant cross section for the h–h collisions at energies

$$s^{1/2} = [2nm_N E_p^{in} + n^2 m_N^2 + m_h^2]^{1/2}.$$

In Fig. 1 the solid lines represent the results of calculations for the spectrum of π-mesons produced in the interaction of protons ($E_p^{in} = 8.4$ GeV) with nuclei C^{12}. The comparison with experiment shows that the model of "coherent" tube gives the

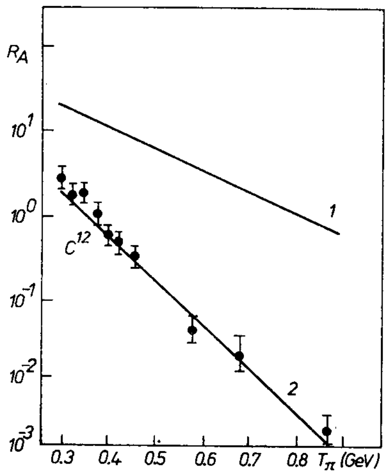

Fig. 1. Invariant cross section $R_A(T_\pi) = F$. The curve *1* is the calculation by the model of tube

yield of π-mesons higher than by an order of magnitude. Moreover, even qualitatively, the model does not reproduce the observed regularities.

Fig. 1 shows an incorrect slope of the spectrum of π-mesons. Furthermore, with increasing A the discrepancy with experiment becomes larger. This is clearly seen in Fig. 2,

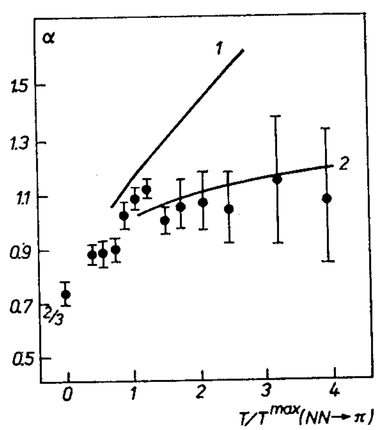

Fig. 2. Dependence $\alpha(T_\pi/T_{\pi,NN}^{max})$ in the expression $R_A(T_\pi) \sim A^\alpha$. The curve *1* is the calculation by the model of tube

in which the model predictions (solid line) are compared with the data for the A-dependence of cumulative π-meson yield.

Therefore, the extremely collectivized mechanism of the interaction of hadron with nucleus, which forms the basis of the model of "coherent tube", cannot be the dominating channel. The upper limit of the probability for its realization is close to 0.05. Thus, attempts to use this mechanism for describing the basic characteristics of hadron-nucleus interactions [11] are not reasonable.

3. *The model of "tube" and production of $\mu^{\pm}$ pairs on nuclei*

The validity of the asumption on simultaneous interaction of hadron with n nucleons of the tube can be checked by comparing the predictions concerning the production of pairs in the hadron-nucleus interactions. Indeed, if this mechanism is realized, the kinematic limit for the effective mass of $\mu^{\pm}$ pair is defined by the expression

$$m_{\mu^+\mu^-}^{\max} = [2nm_{\rm N}E_{\rm p}^{\rm in}+(n^2+1)m_{\rm N}^2]^{1/2}-(n+1)m_{\rm N}. \qquad (4)$$

It is seen from (4) that the kinematic limit in the case of "coherent tube" should increase strongly. However, the experimental data on the production of $\mu^{\pm}$-pairs in the p$-$U interactions [21], which are reproduced in Fig. 3, show that the kinematic limit differs

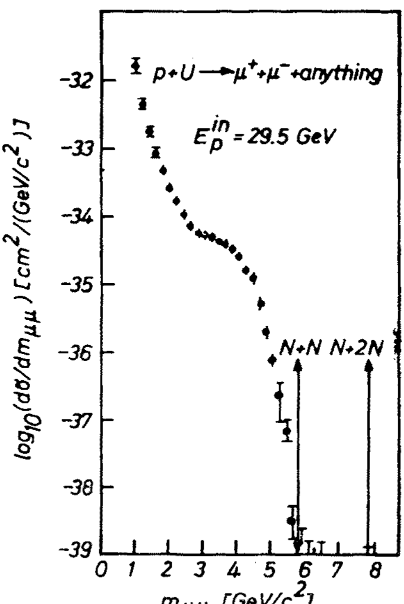

Fig. 3. Spectrum of effective mass of $\mu^{\pm}$ pairs

slightly from its value for the p$-$p interactions also in this case. Hence, it follows that the situation characteristic for the mechanism of tube is realized in a negligible number of cases[2].

[2] This conclusion was first made in paper [22] while discussing the cumulative processes.

Unfortunately, this problem is not discussed in [14], and when comparing their results with experiment they neglect all the range of values $m_{\mu^+\mu^-}$ near the kinematic limit. Therefore, the conclusions [14] about the realization of the mechanism of tube are not convincing.

4. The model of tube and production of particles with large $p_\perp$ on nuclei

In paper [12] the model of "coherent tube" is used to describe the production of particles with large $p_\perp$ in collisions of protons with nuclei at energies $E_p^{in} = 200$ and 300 GeV [23]. It was shown that a satisfactory description of A-dependence of π-meson yield can be achieved only in the range of values $p_\perp \leqslant 3$ GeV/c. At large $p_\perp$ the results of the calculations strongly disagree with experiment. Fig. 4 shows these results [12] and the experimental data [23]. This is not the only difficulty. To be convincing we consider

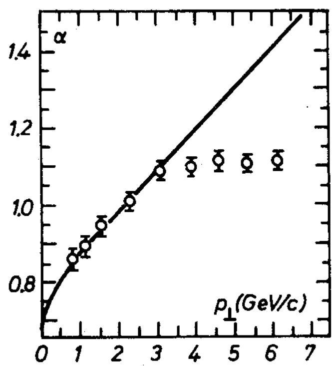

Fig. 4. Dependence $\alpha(p_\perp)$ in the expression $R_A(p_\perp) \sim A^\alpha$. The solid curve is the calculation by the model of tube

the invariant cross sections of produced particles. In the interval under consideration in 0.76 GeV/$c \leqslant p_\perp \leqslant 6.1$ GeV/c they decrease by many orders (8−10!) both in p−p and p−A collisions. The role of the nucleus in the production of particles with large $p_\perp$ is clearly seen from the relation

$$f = (\sigma_{pp}^{in}/\sigma_{pA}^{in})\left(E\frac{d^3\sigma}{dp^3}\right)_{pA}\Big/\left(E\frac{d^3\sigma}{dp^3}\right)_{pp} \tag{5}$$

as a function of $p_\perp$. For convenience we normalize (5) to unity both for the experiment and theory at point $p_\perp = 0.76$ GeV/c, which is the lower limit of region $p_\perp$, in which the measurements have been made [23]. It is seen from Fig. 5 that the experimental relation (5) increases with increasing $p_\perp$. This figure also shows the results of calculations for the model of "coherent tube", using relations (1)—(3). As F_0 we have used the data of paper [23]. It is seen that the conclusions from the model are in contradiction with experiment. The role of the collective interaction appears to be greatly overestimated. Consequently, this experiment also does not confirm the hypothesis which is used as the basis for the model of "coherent tube".

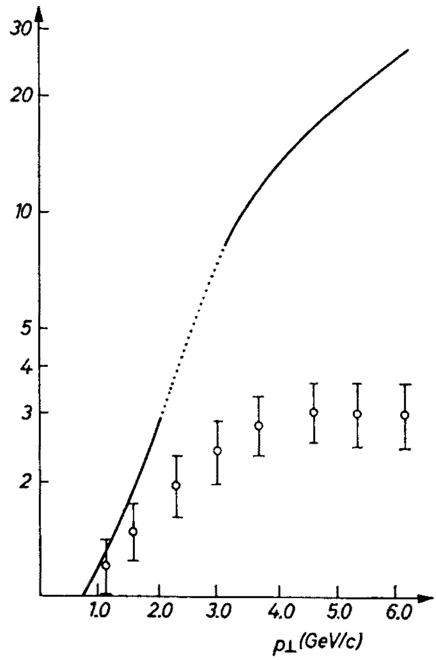

Fig. 5. Dependence $\frac{R_p(0.76)}{R_A(0.76)} \cdot \frac{R_A(p_\perp)}{R_p(p_\perp)}$ for the titanium nucleus. The solid curve is the calculation by the model of tube

5. *Conclusions*

The comparison of the predictions of the model of "coherent tube" with the experimental results, which are crucial to its basic assumption, justifies the following conclusions:

1. These assumptions are in contradiction with the experiments in a wide energy interval (several GeV — hundreds GeV).

2. The assumption concerning a simultaneous interaction of an incident hadron with all the nucleons which are in the tube with the cross section σ_{NN}^{in} lying along its motion, does not correspond to the observations.

3. The results of calculations within the model of tube coincide with experiment in some characteristics relating to the basic channel. This coincidence in the hadron-nucleus interaction is accidental as this mechanism is realized (if at all it is realized) with very small probability.

4. The same conclusions can be made about the parton models for the hadron-nucleus interactions which use the concept of tube [24]. The increase of the longitudinal dimensions in the interaction region, for instance $\sim E^{1/2}$ [25] or $\sim E$ [26], predicted by certain versions of the parton models, is not observed in the considered energy interval. From this point of view the idea concerning the longitudinal structure of a hadron in the parton model [27, 28] is preferable.

Thus, the model of "coherent tube" is in extreme contrary to that of the cascade model. Like the latter, we think it does not correspond to the situation realized in the hadron-nucleus processes. Therefore, one should always take into account the space-time development of the interaction of relativistic hadron with the nucleus without over simplifications as was done in the aforementioned models.

One of the approaches that realistically accounts for the finiteness of the space-time interval is the model given in [8–10]. In Figs. 1, 2 the results obtained within this model are denoted by curves with index "2". In this case a good agreement with the experimental data is obtained by taking into account the finiteness of the interval.

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